Crew-Centered Operations:
What HAL 9000 Should Have Been

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To date, manned space flight has maintained the locus of control for the mission on the ground. Mission control performs tasks such as activity planning, system health management, resource allocation, and astronaut health monitoring. Future exploration missions require the locus of control to shift to on-board due light speed constraints and potential loss of communication. The lunar campaign must begin to utilize a shared control approach to validate and understand the limitations of the technology allowing astronauts to oversee and direct aspects of operation that require timely decision making. *Crew-centered operations* require a system-level approach that integrates multiple technologies together to allow a crew-prime concept of operations. This paper will provide an overview of the driving mission requirements, highlighting the limitations of existing approaches to mission operations and identifying the critical technologies necessary to enable a crew-centered mode of operations. The paper will focus on the requirements, trade spaces, and concepts for fulfillment of this capability. The paper will provide a broad overview of relevant technologies including: Activity Planning and Scheduling; System Monitoring; Repair and Recovery; Crew Work Practices and Processes

I. Introduction

The current operations models used in Station and Shuttle, which require large ground teams and on average 500,000 ground-generated system commands per year [vi], are a major cost driver for these programs and cannot extend beyond the Earth-moon neighborhood (due to communications time-delays). Even for lunar missions, the cost and mode of on-board operations must be dramatically changed in order to achieve NASA's exploration goals. For this reason "autonomy" – making flight crews more autonomous from ground controllers – is one of the original Exploration Systems Research and Technology (ESR&T) program's "grand challenges".

Crew-centered operations is an alternative mission operations paradigm in which astronauts are given full awareness of spacecraft and habitat status, the authority and ability to proactively plan future activities, and the ability to react to events and anomalies by commanding Crew Exploration Vehicle (CEV) systems and adjusting their own activities. The crew becomes the center of all operations – rather than a receiver of directives from the ground. This achieves dramatically changed on-aboard operational capabilities, probable reduced operations costs, and scales naturally to operations on Mars (where light speed communications delays dramatically limit the role of the ground).

Crew centered operations is a complex challenge because it means that the crew must be able to track and modify daily activity plans, monitor key systems, isolate anomalies, and select and perform any required recovery procedures. Further, the crew must do this while cross-trained for multiple other tasks

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and while still fulfilling their other mission responsibilities (e.g., unlike in traditional ground-based operations there cannot be a crew member permanently assigned to monitor life support, power, or other systems). This will only be possible if appropriate automation and autonomy technology is seamlessly integrated into operational procedures so that all the information required to make key decisions is continuously updated and presented to the crew in a rapidly comprehensible fashion.

Over the past decade NASA has made significant progress in developing and demonstrating the technologies needed for crew-centered operations: human-centered systems and interfaces, planning and scheduling, system fault diagnosis and recovery, procedure representation and reactive task execution. Successes include ground-based automated scheduling for Space Shuttle operations in the Orbiter Processing Facility at Kennedy, constraint-based activity planning for the MER rovers (the MAPGEN[i] system), a wide-area operations and collaborative data system for exploration (MERCIP[ii] and MERboard for MER), fail-operational autonomous on-board control for an interplanetary spacecraft (Remote Agent Experiment[iii]) and onboard model-based diagnosis (Livingstone 2 on EO1).

The need for increased onboard autonomy is reflected in the ongoing discussions of Exploration Systems Mission Directorate requirements. For example, given the predicted communication latencies, and periodic communication lapses, we expect the CEV requirements to call for onboard capabilities allowing the crew to recognize, isolate, and correct critical system malfunctions independent of ground systems. Further, we expect to see a significant increase throughout the CEV spirals in the requirement for onboard autonomous operations throughout the missions.

The NASA mission community tends to be properly conservative about the use of new technology in mission-critical, and life-critical, situations. The automation necessary to support crew-centered operations is correctly perceived as involving new technology. Consequently, a realistic way to create acceptance of this new technology is to perform a series of analog demonstrations, and then to begin using the technology in CEV missions as soon as practical.

In order to meet these CEV requirements it is critical that crew-centered operations are assumed from the beginning of the CEV development process. Operations concepts have system-of-systems implications for mission design, and tend to become "baked" into mission design and culture. The difference between crew-centered operations and ground-centered operations, for example, impacts crew size, telemetry rates, buffer sizing (e.g., for oxygen), avionics design (e.g., onboard computational horsepower), software development budgets, operations budgets, assumptions about crew time availability, crew training, etc. It is extremely difficult to take a system designed for ground-centric operation (e.g. Station) and retrofit for crew-centered operations. For this reason it is essential that crew-centered operations is utilized as early as possible in the CEV spirals.

One important thing to keep in mind is that we must operate ESMD Lunar precursor missions in the same way that we will operate ESMD Martian missions. That is, we should not take operations "short cuts" that are possible on the Moon but not possible on Mars. Clearly, we do not propose to introduce additional unacceptable safety risks for Lunar precursor missions, but to the greatest possible extent, it is important to design the operations model for Lunar precursor missions in a way that also teaches us important lessons for operating Mars missions.

II. Lunar Mission Operations Element Trades

In order to understand how crew centered operations will impact and be impacted by the various mission profiles, we need to create trade-trees that characterize operations model alternatives for ESMD missions. See Figure 1 for a trade-tree that is organized around the objective (or Figure Of Merit) of maximizing Crew Exploration Vehicle (CEV) independence. The 'input' to this trade-tree is a classification of the category of analysis to be conducted or decision to be made, and a commitment to a detailed point in a mission profile during which the analysis or decision is to be made.

For example, does the decision have to do with crew activity planning, or life support? Is the mission phase trans-Earth injection, cruise, or Lunar descent? Different kinds of decision / analysis at different points in a mission's profile call for different kinds of response with respect to where and how computers and 'automation' are expected to help provide an accurate, safe, and timely response.

The trade-tree in Figure 1 attempts to maximize CEV independence, which may or may not be the right thing to do. Maximizing CEV independence is good in that it could lead to an operations infrastructure that is expected to help efficiently achieve mission objectives under a wide variety of circumstances, but it could also be extremely expensive and introduce unnecessary complexity.

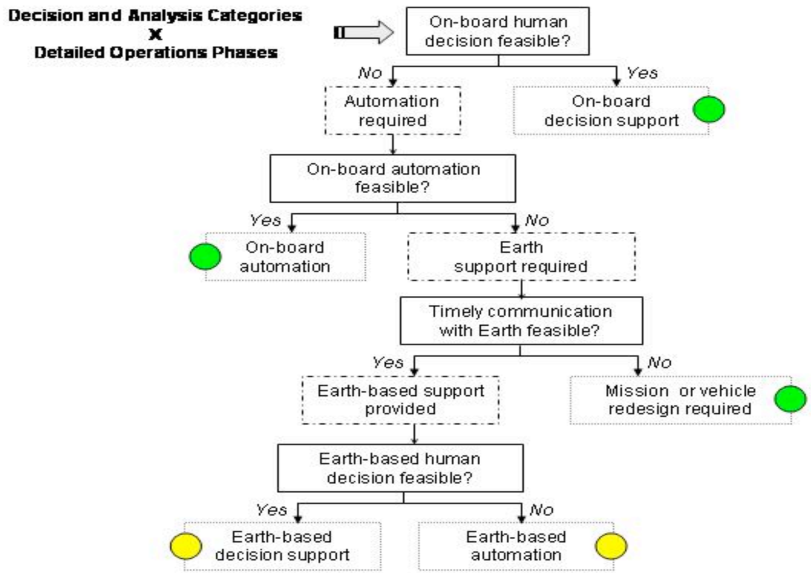

Figure 1: Trade-tree organized around the objective of maximizing CEV independence. Green circles represent trade-tree exit points that should be studied with high priority, and yellow circles are medium priority.

Figure 2 shows an alternative trade-tree, this time organized around the objective (or Figure Of Merit) of utilizing Earth-based support to the greatest possible extent. The input to this trade-tree is the same as shown in Figure 1, but the results are quite different. This time, whenever it's possible to leave a decision or analysis on Earth, that's what's done. This approach will likely yield an operations infrastructure that's cheaper and quicker to construct, but the CEV will probably be less effective at using available time, and will possibly be too dependent upon help from Earth.

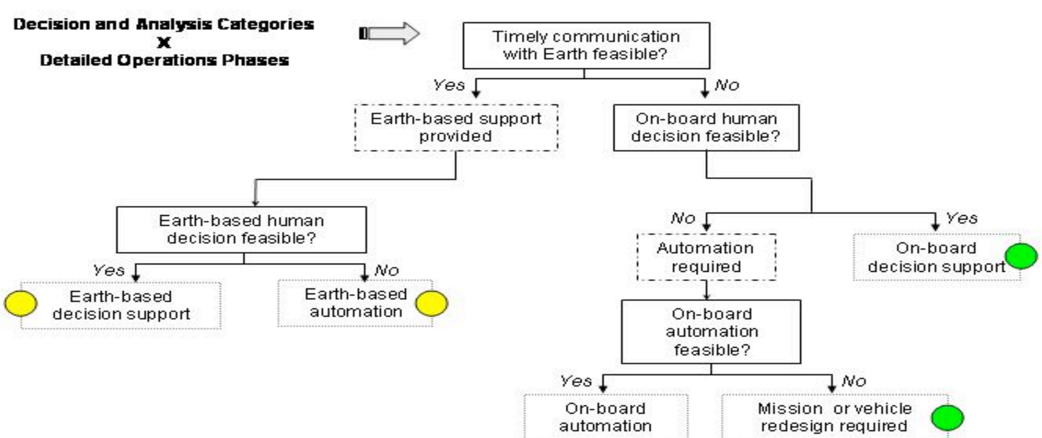

Figure 2: Trade-tree organized around the objective of utilizing Earth-based support. Green and yellow circles represent trade-tree exit points that should be studied with high and medium priority.

Figure 3 provides a summary of the 'exits' in both trade-trees, and indeed, a summary of exits from all possible trade-trees. While many other trade-trees are possible, based on alternative objectives, all will eventually produce guidance regarding where a decision should be made, and how humans and computers participate together in making that decision (alternatively, where an analysis should be conducted, and how humans and computers do that analysis).

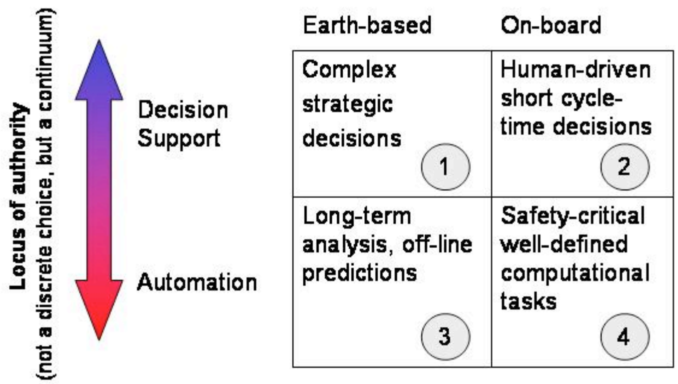

Figure 3: Exits in the trade-trees shown (and others) can be organized into four sorts of outcome. While in reality the vertical axis is a continuum and not binary-valued, this organization of the trade-tree exits helps provide a framework for considering the trade-offs identified in each trade-tree.

The "Locus of authority" axis in Figure 3 characterizes the interaction between Human and machine. While the figure shows the continuum as a binary outcome, there's clearly a wide range of alternatives at work. Humans can be in charge of decisions, and the machines can provide decision support, calculating ramifications of decisions made by Humans; or the system can be more towards the "fire and forget" end of the continuum, where Humans provide targets or reference signals for vast tracts of the expected operable space, and are only asked for input / guidance in special or extreme circumstances. The trade-tree outcomes in Figure 3 characterize all the options for localizing the making of decisions, and different trade-trees weight and prioritize these outcomes in different ways. For the discussion in this paper, we have considered only two such prioritizations here. There are alternate trade-trees that could be developed. Studies are underway to both characterize the tradeoffs in mission autonomy and create the basic data sources needed to make these decisions in a principled fashion [vii].

III. New Operations Modes for Exploration Missions

We believe that with reasonable research funding, crew-centered operations can be demonstrated at TRL 6 in the 2010 timeframe. This is sufficiently early to allow the technologies to be operationally baselined in Spiral 2, which will, in turn, allow the technology to be fully exercised and validated on the moon to prove its utility for the subsequent Mars missions. Maintaining this technology development schedule and the required budgets will be essential in realizing the major overall system cost savings from designing exploration missions using proven crew-centered operations.

It should be made clear that when we discuss "technology for crew-centered operations" we are actually referring to a host of related technologies in information integration and synthesis, command and control, automated monitoring, fault isolation, fault recovery, mixed-initiative planning and scheduling, automated 'just-in-time' training, situational awareness, human/machine interface design, etc. It should be noted that not all of these technologies will mature at the same rate. Thus what we will see in practice is an adoption of automation and autonomy technologies in Spirals 1-4, leading to true crew-centered operation in Spiral 4. Prior to Spiral 4, the crew will always be in the vicinity of the Earth and have low-latency, high-bandwidth communications with the ground to enable an ISS-like ground operations model to function. Once in Spiral 4 and in interplanetary space, crew-centered operations is no longer an option, but is mission-critical. The reality of gradual migration, because of the time lag required for technology maturation, the vetting of the technologies in the Earth-moon vicinity, and the conservatism of mission designers, is one of the key reasons for starting this research as soon as possible.

HAL 9000 can be viewed as a science fiction view of what this mode of operation might have looked like. However, in 2001 HAL 9000 was designed as a completely autonomous system that could independently make decisions. As we embark upon the future of joint human/robotic exploration, we don't need technology that attempts to automate human reasoning. Instead, our challenge is to develop technology that can augment and enhance unique human abilities and are centered around these capabilities. Crew-centered operations emphasizes that the technology must be developed in concert of a vision of the role of the astronauts with the crew members controlling the locus of control and directing the activities of the mission.

Accomplishing this vision is truly a grand challenge of the research community as it requires the development of systems that reason about complex system behavior while also seamlessly interacting with the human crew that are controlling the mission. Of course, there has been a great deal of progress over the years in this area, but much more is still required. The key challenge is understanding how various reasoning capabilities can be integrated into a truly intelligent *system.*

Our goal as a community should be to develop and demonstrate the tools and systems for crew-centered operation for use in the CEV systems. This will show that crew-centered operations can be baselined in CEV Spirals 2+ without sacrificing safety and with increased efficiency and affordability for the Constellation SuperSystem.

The work breaks down into several parts: the creation of flight scenarios, the creation of models for the relevant CEV systems at some level of fidelity, the development of the software necessary to support crew-centered operations, execution of the simulated scenarios, and analysis of the results. The creation of relevant CEV-analog flight scenarios[iv] is a key step and must be done in close collaboration with the ESMD requirements division. Model development is potentially an expensive proposition. As will be seen below, our belief is that models can be developed at moderate fidelity in the areas where precise modeling (e.g., refining the current draw of the CO2 scrubber from 2 Amps to 1.9 Amps) is unlikely to materially affect the challenges in crew-centered operations.

The key technology development areas are:

- **Activity planning and replanning**: For Station (and presumably also for CEV) the planning and scheduling of attitude, communications, power systems, environmental control, life support systems, and crew activities interact quite closely and, indeed, are developed concurrently by large ground teams. This poses an interesting problem for crew-centered operations since the integrated activity plan will need to be regularly modified (and perhaps developed) onboard.
- **System monitoring**: In Station and Shuttle operations, a major role of ground controllers is to monitor critical systems and identify problems before they become life threatening. Clearly this cannot be a full-time job for the flight crew. Further, both to ensure affordability and to enable operation beyond the earth-moon neighborhood, these activities cannot continue to be done by large ground teams.
- **Repair/recovery**: A wide range of CEV situations will require moderate changes to the crew's pre-planned activities (without being sufficiently dangerous to require a complete stand-down and urgent message to Earth). These include failure of primary systems which have a running backup, load shedding (e.g., because solar-panel sun lock has drifted), unexplained readings on key equipment, etc. In these cases the crew will require automated assistance for rapid situational awareness, root cause analysis, the selection of appropriate recovery procedures, and the incorporation of those recovery procedures into the day's plan.
- **Crew work practices and processes**: On both Station and Shuttle, the crew's activities are tightly coordinated by the ground. Modifications in planned activities and on-orbit operations such as telerobotics control, or even maintenance procedures, are carefully coordinated by ground operations control[v].

In allocating resources for this effort the major variables are: the level of modeling fidelity, the duration of the simulated missions, the number of CEV systems which will be modeled (and thus also planned and monitored), and the amount of component technology development that will be supported. As noted above, to have crew-centered operations systems ready for lunar testing and fully flight certified for use on Mars missions, it is critical to be at an overall TRL 6 level for this suite of technologies by 2010.

IV. Conclusions

We must operate ESMD Lunar precursor missions as we plan to operate ESMD Mars missions. While it is unacceptable to introduce 'artificial' safety risks to do this, we should organize our mission operations for Lunar precursor missions in a way that generates the best possible lessons for subsequent missions to Mars.

Based on anecdotal experience with Shuttle and ISS, flight controllers account for less than 1% of the total program budgets. This appears to be a likely outcome for ESMD missions, too. Thus, reducing basic headcount of flight controllers is not likely to result in a significant cost reduction for ESMD missions. However, communication latencies will necessarily limit the role of the ground in the operations of Mars missions and we must anticipate these limitations in the design and execution of both the ESMD missions and systems.

We must decide upon an overall operations objective (or Figure Of Merit) that will serve as a guiding principle for constructing a trade-tree for ESMD missions, one that is defensible in terms of mission cost, safety, and overall performance. We must agree on this overall operations objective early on, or significant problems will result.

Once we have ESMD mission architectures in hand, and with an appropriate overall operations objective, we can begin to decide how to invest to achieve that objective. Possible technology investment areas include, but are not limited to, on-board decision support, automation, and training (including processes, procedures, etc.), and Earth-based decision support, automation, and training.

A further "meta objective" should be to maximize system flexibility over time. Where we start will not be where we finish. We will learn a lot about what sorts of decisions can and should be made on-board the CEV, even if we start by making those decisions on Earth. Thus our system (technology, processes, people, etc.) should support the clean and incremental migration of decisions to the CEV, as and when appropriate. We must avoid architectures that "box us in" with respect to where and how certain classes of decisions are made. Of course, achieving this flexibility comes at a cost. Trading the cost of such flexibility against other places to spend money will be an important element to consider, early on.

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